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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Harry Diamond Laboratories (HDL) has developed an air-driven alternator as a low-cost, easily manufacturable power supply for the M734 multi-option fuze for mortars (750,000 have been produced to date). As a result of this program, HDL has acquired the technical capability of producing alternators of similar design to meet a wide range of fuze power requirements for other mortar, bomb, and artillery applications.

20. ABSTRACT (Cont'd)

Design features of alternators for these applications are discussed. These include methods of achieving velocity discrimination, enhancing bearing life by limiting shaft rotational speed at high projectile velocities, increasing power output with high-energy samarium-cobalt magnets, and strengthening the design for artillery environment.

CONTENTS

FIGURES

FIGURES (Cont'd)

FIGURES (Cont'd)

1. INTRODUCTION

As a result of the development of the alternator for the multi-option mortar fuze, the power supply group at Harry Diamond Laboratories (HDL) has acquired the capability of designing similar alternators that can meet a wide range of Army, Navy, and Air Force fuze power requirements.

The purpose of this report is to describe HDL's capability in this area. The basic features of several alternator designs are discussed, including the means of achieving various power levels, reducing alternator size, limiting rotational speed, attaining velocity discrimination, and using improved magnetic materials. Representative laboratory and field test results that show the suitability of these designs for several fuzing applications are described.

2. THEORY OF OPERATION

2.1 Application to Mortars (M734)

The alternator as originally developed for the M734 multi-option fuze program has been described.[1,2,3] The M734 multi-option mortar fuze developed for use on the new Army light-weight company mortar employs the ram air-driven alternator as the power supply. The alternator provides air velocity as a second safety signature to satisfy MIL-STD-1316A/B. During flight air is directed to a turbine mounted on a shaft that is common to a concentrically mounted permanent-magnet rotor. The spinning turbine drives the magnet to switch the flux through a permalloy stator, thus inducing an emf in the surrounding coil. In addition, the concentric shaft extends through the alternator and terminates in a screw-driver-like slot that engages with the safing and arming (S&A) system. This arrangement drives a gear train that unlocks the rotor. A spring then forces the rotor from a safe out-of-line position to the armed in-line position. After mechanical arming, usually within the first 328 ft (100 m) of flight, the alternator shaft is disengaged from the S&A to provide full electrical power. Thus, the alternator provides both mechanical and electrical energy for the fuze.

The alternator design has evolved from several laboratory design iterations containing machined parts and miniature precision bearings to the present low-cost production design. In this version (fig. 1), the two-piece

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[1]*Carl J. Campagnuolo and Jonathan E. Fine, Development of the HDL Air-Driven Rotary Generator to Power a 60-mm Fuze, Harry Diamond Laboratories, HDL-TM-72-8 (March 1972).*

[2]*Carl J. Campagnuolo and Jonathan E. Fine, Development of an Air-Driven Alternator for 60-mm Mortar Application - Phase II, Harry Diamond Laboratories, HDL-TM-73-7 (May 1973).*

[3]*Chris E. Spyropoulos, Development of an Air-Driven Alternator for the XM734 Light-Weight Company Mortar Fuze, Harry Diamond Laboratories, HDL-TM-77-31 (October 1977).*

stator and bearings are stamped from progressive dies. The shaft, which forms the bearing inner race, is cold formed. The alnico-2 sintered magnet is molded onto the shaft with a thermoplastic. The turbine and bobbin are molded from nylon 101, and the coil is a simple winding. This has resulted in a low-cost design that is state-of-the-art in fuze technology. To date about 750,000 units have been produced.

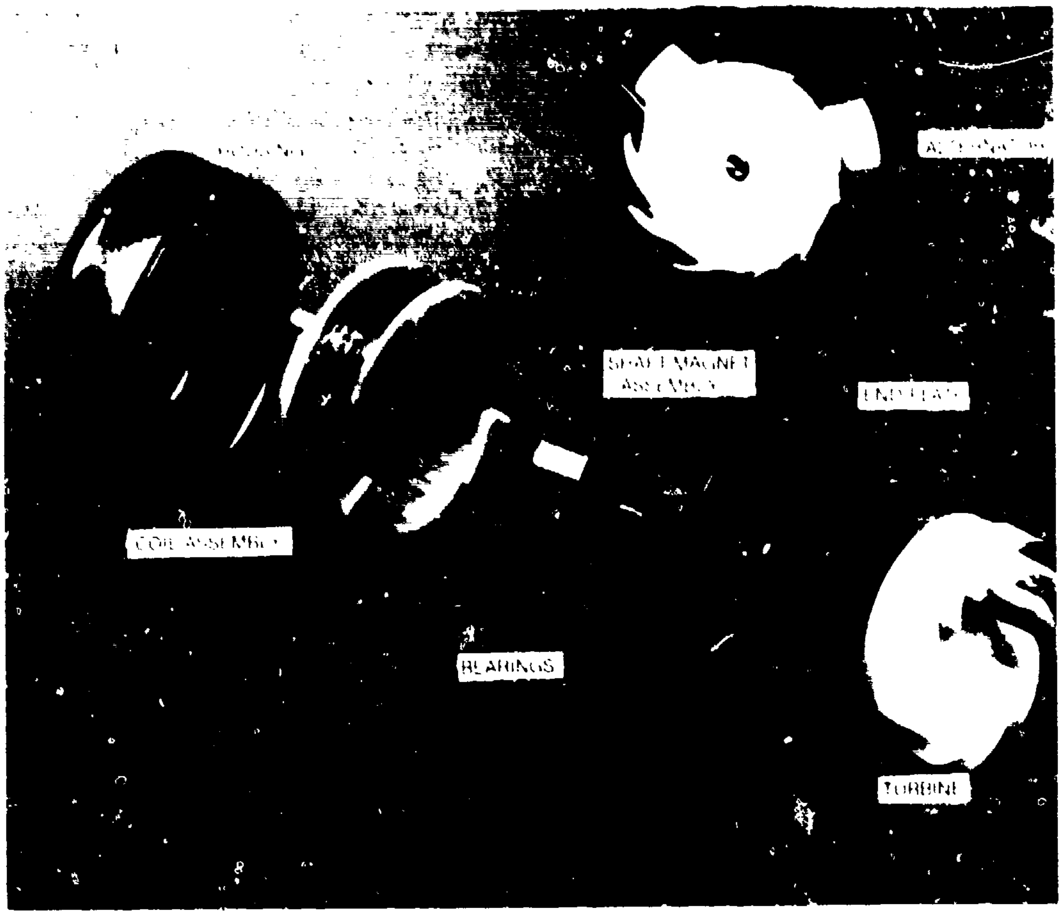

Figure 1. Turbine-alternator used in M734 fuze (top): exploded view showi component parts (bottom).

2.2 The Turbine as a Aerodynamic Power Source

During flight, ram air enters the fuze housing through an intake duct, impinges axially on the turbine, and is diverted laterally by the blades (fig. 2). The reaction from the change in fluid momentum produces a torque that drives the wheel.[4] The dependence of this torque, T, on the mass flow of fluid through the blades and the angle, $_2$, that the departing flow makes with the trailing edge of the blades is given by[1]

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[1]*Carl J. Campagnuolo and Jonathan E. Fine, Development of the HDL Air-Driven Rotary Generator to Power a 60-mm Fuze, Harry Diamond Laboratories, HDL-TM-72-8 (March 1972).*

[4]*D. C. Shepard, Principles of Turbomachinery, The MacMillan Co., NY (1956), p 51.*

$$T = \dot{m} r_2 (V_{r_2} \cos \beta_2 - \omega r_2) , \qquad (1)$$

where:
r_2 is the radius to the blade tip,
ω is the angular velocity of the turbine, and
V_{r_2} is the air velocity relative to the blades at the trailing edge.

The relationship among these parameters is shown in the diagram of figure 3.

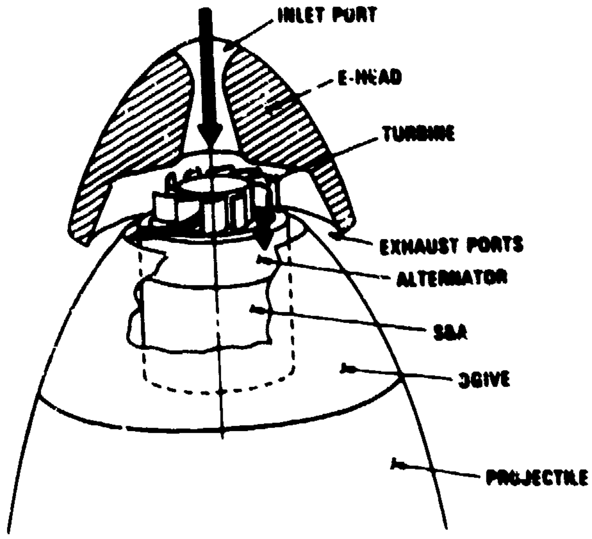

Figure 2. Artist's sketch of M734 fuze mounted on projectile emphasizing airflow through inlet and exhaust ports and turbine blades.

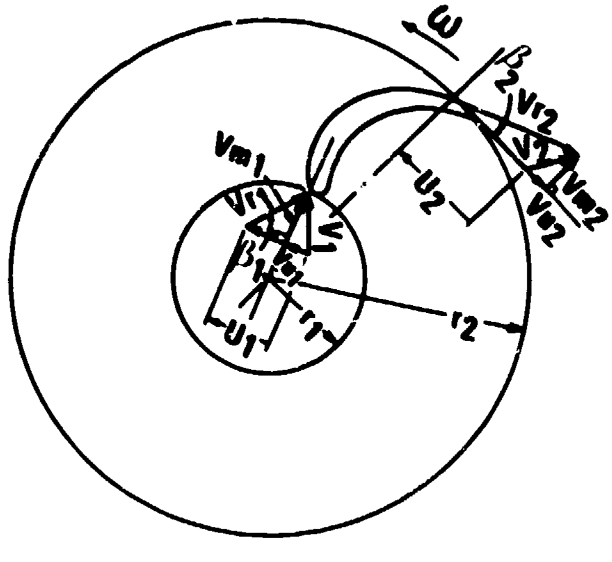

Figure 3. Turbine blade showing velocities considered in analysis.

Equation (1) shows that the maximum torque would be produced if

$$\beta_2 = 0 . \qquad (2)$$

This would correspond to the blade tip's curving enough so that the flow would leave tangent to the rim of the turbine. Figure 4 is a photograph of the

turbine for the alternator of the M734 fuze for which the blade configuration was optimized experimentally. It is clear that although the blades are curved, they do make an angle (about 30 deg) with the rim so that the theoretically optimum torque is not achieved. This compromise was necessary to minimize the interference of the flows between adjacent turbine blades.

Equation (1) also shows that the torque decreases as a result of two effects: an increase in β_2 or an increase in rotational speed, ω. The angle, β_2, could increase, for example, if the blade were slightly flexible and could bend out under the influence of centrifugal force. This furnishes a method of limiting the rotational speed that will be explored later in this report. The rotational speed can increase until a theoretical maximum value is reached such that

$$\omega_{max} = \frac{V_{r_2} \cos \beta_2}{r_2} . \qquad (3)$$

At this speed, the applied torque would be zero, and the turbine would maintain constant rotational speed.

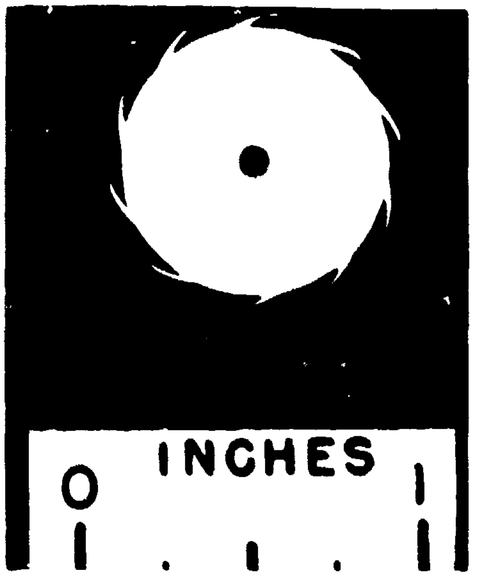

Figure 4. Turbine used with alternator for M734 fuze.

To calculate the torque one must know the fluid velocity V_{r_2}. In practice, this quantity is difficult to calculate because it is a function of the flow pattern and depends on the blade configuration and duct design. The propeller design was therefore developed by an experimental approach based on the abovementioned theoretical considerations.[1] The turbine wheel for the alternator used with the M734 fuze is shown in figure 4.

2.3 Magnetic Circuit

The rotational motion of the shaft, produced by air impinging on the turbine wheel, is converted to electrical energy by the stator magnetic circuit. The magnetic circuit contains a magnet rotor, a stator, and a coil.

In an alternator such as that used in the 60-mm mortar, the rotor consists of a magnet with six poles that is centrally located between the pole pieces of the stator (fig.5). Each casing contains three pole pieces separated by 120 deg between centers. When the casings are assembled, the separation between centers of any two adjacent pole pieces is 60 deg. In this assembly, the coil is placed between the two casings.

[1]*Carl J. Campagnuolo and Jonathan E. Fine, Development of the HDL Air-Driven Rotary Generator to Power a 60-mm Fuze, Harry Diamond Laboratories, HDL-TM-72-8 (March 1972).*

When the turbine wheel is rotating, the magnetomotive force of the magnet transfers flux through the stator, and an emf is induced in the coil winding. For every 120 deg of rotation, the induced emf completes one electrical cycle. Hence, for every 360 deg of rotation, the induced emf completes three electrical cycles.

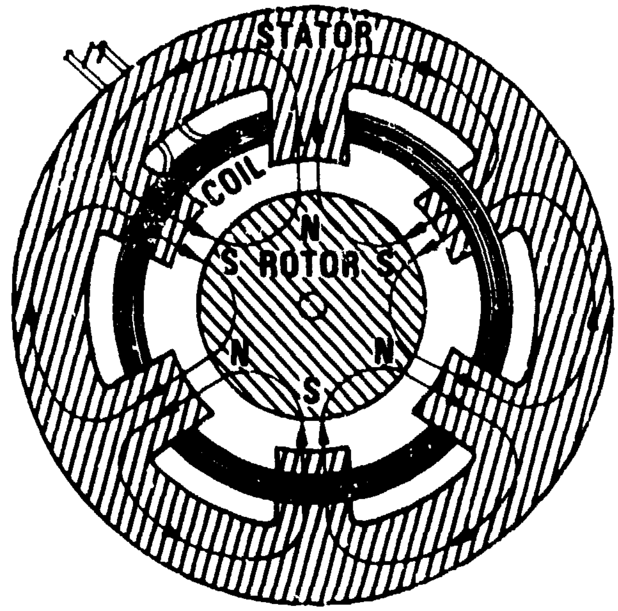

Figure 5. Magnetic circuit of six-pole alternator showing flux path.

This type of magnetic circuit can also be used with two-pole or four-pole alternators. For a two-pole configuration, the rotor and stator each have two poles. For every 360 deg of rotation, the induced emf completes one electrical cycle. In the four-pole configuration, the rotor and stator each have four poles, so that the induced emf completes two electrical cycles for each 360 deg of rotation.

For the rotor to spin, the restoring torque caused by the attraction between each rotor pole and its magnetic image in the corresponding stator pole must be exceeded by an external torque applied to the shaft. This rotor-stator attraction prevents rotation until a predetermined projectile velocity has been achieved, at which time a sufficient angular impulse is supplied by the ram air passing through the turbine. This phenomenon is discussed in more detail in section 4, "Velocity Discrimination."

3. LIMITING ROTATIONAL SPEED AERODYNAMICALLY

For the mortar application, the alternator was designed to meet the fuze electrical and mechanical requirements at the low-flight velocity range of the mortar (150 to 200 ft/s).* However, limiting the rotational speed at the higher flight velocities (400 to 800 ft/s) was necessary to maintain the mechanical arming time within specified limits at all flight velocities and to reduce bearing wear. Several methods for limiting the rotational speed, presented below, can be used in applications where the rotational speed must be restricted.

3.1 Flower Method

An early method, which was successfully field tested, employed a metal flower containing several petals mounted within the turbine (fig. 6). At low velocities, the flower petals are wrapped around each other in the

*(ft)0.3048 = (m)

center of the turbine. At a set turbine rotational speed, centrifugal force opens the petals that then block the flow through half of the turbine blades, thus restricting the rotational speed. The turbine used in this application had 12 blades.[1] In figure 7 the rotational speed versus inlet velocity, as measured in the laboratory, is shown for an alternator without the speed reducer and for an alternator having a speed reducer with petals fully deployed. The rotational speed in this case is limited over the entire velocity range by the deployed petals. At an inlet velocity of 700 ft/s, the rotational speed was reduced from 119,000 to 94,000 rpm. The flower speed-limiter concept was discarded in favor of a simpler design.

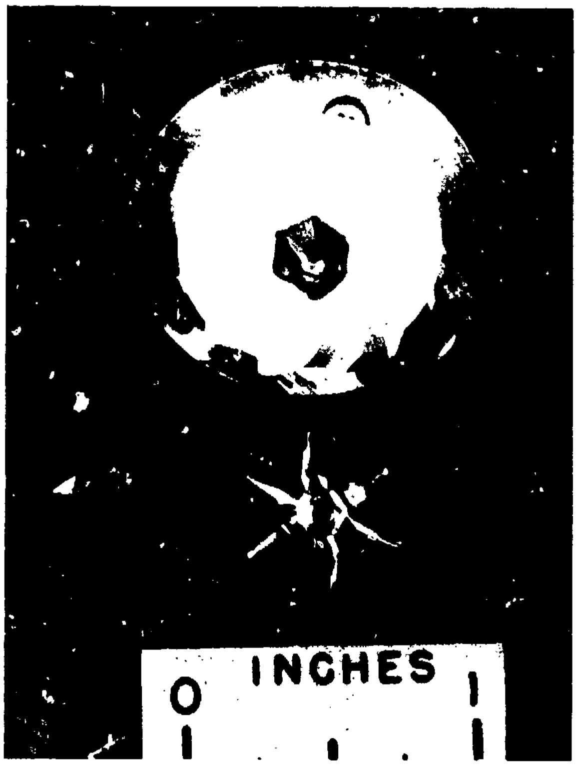

Figure 6. Alternator with speed reducer using petals that open under centrifugal force.

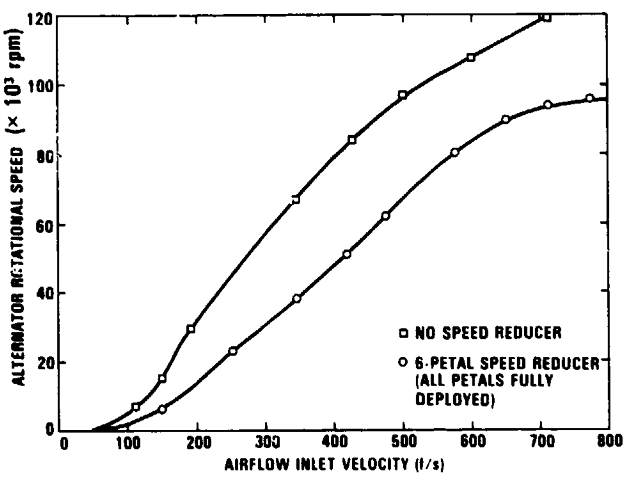

Figure 7. Effect of flower speed reducer with petals fully extended on rotational speed over velocity range of 60-mm mortar.

[1]Carl J. Campagnuolo and Jonathan E. Fine, *Development of the HDL Air-Driven Rotary Generator to Power a 60-mm Fuze*, Harry Diamond Laboratories, HDL-TM-72-6 (March 1972).

[2]Carl J. Campagnuolo and Jonathan E. Fine, *Development of an Air-Driven Alternator for 60-mm Mortar Application - Phase II*, Harry Diamond Laboratories, HDL-TM-73-7 (May 1973).

3.2 Extended Blade Turbine Having Undercut Blade Tips

The turbine used in early alternator designs contained 12 blades.[2] A new turbine was developed to increase alternator output. This turbine contains 10 blades designed so that the flow undergoes a larger turning angle. With this turbine (fig. 4), the alternator output was increased up to 50 percent. The tips of the turbine blades were undercut so that they would flex out under the influence of centrifugal forces at higher rotational speeds. Blade flexing reduces the turbine torque by reducing the turning angle of the fluid passing through the blade channels, as shown in figure 8. This in effect increases β_2 in equation (1).

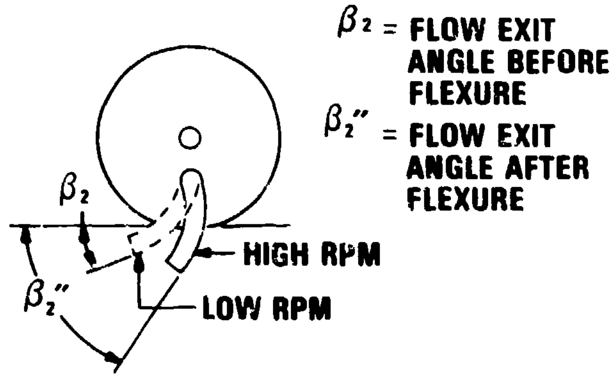

Figure 8. Effect of turbine blade tip flexure at high rotational speed on turning angle of airflow through blades.

The rotational speed versus ram air velocity is shown in figure 9 for the 10-blade turbine with and without the undercut. Rotational speed was reduced by 22 percent at the high velocities (450 to 800 ft/s), and by 10 percent at 200 ft/s, but was not noticeably affected below 150 ft/s.

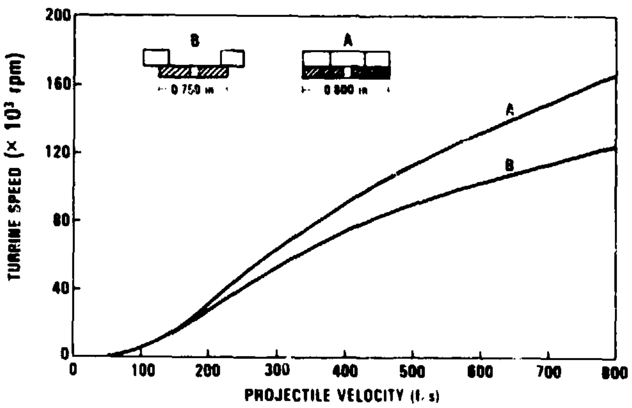

Figure 9. Rotational speed versus ram air velocity.

[2] *Carl J. Campagnuolo and Jonathan E. Fine, Development of an Air-Driven Alternator for 60-mm Mortar Application - Phase II, Harry Diamond Laboratories, HDL-TM-73-7 (May 1973).*

The undercut method of speed reduction is presently being used in the alternator for the M734 multi-option fuze for mortars. This method has the advantage of achieving speed reduction by modifying the turbine itself, and hence, in contrast to the flower design, does not require an extra component.

3.3 Venturi Method

Reduction in rotational speed can be achieved by using a venturi-shaped inlet duct to supply the turbine. A venturi is a duct with an inlet and outlet port of approximately the same cross section, but a reduced cross-section area in the throat (fig. 10).

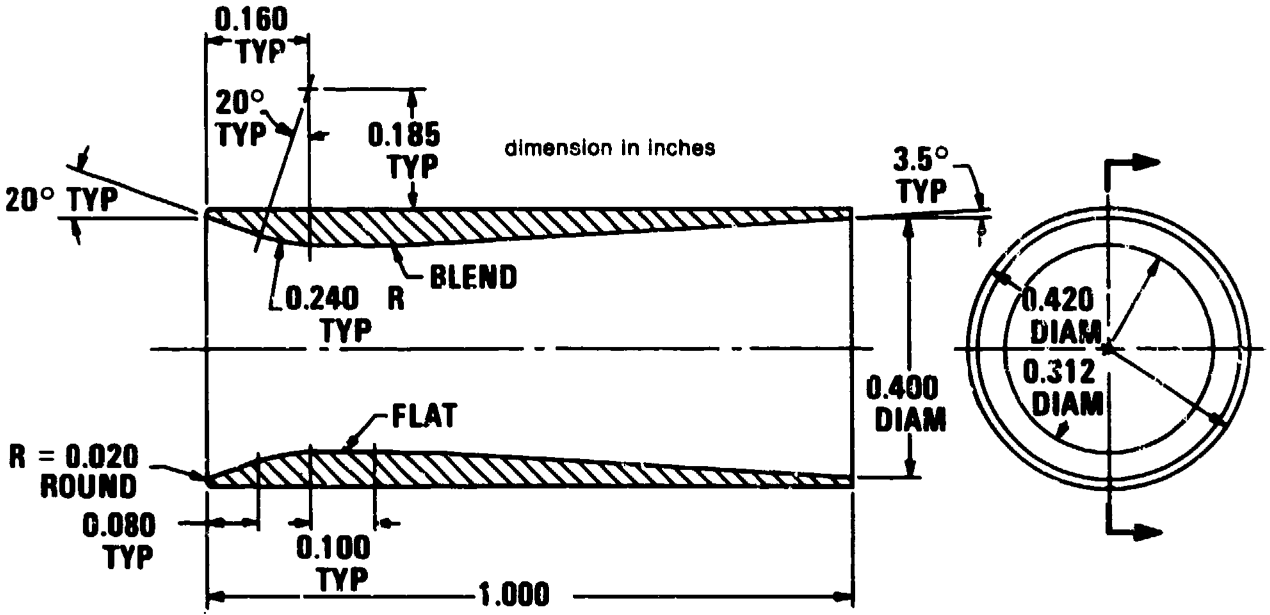

Figure 10. Dimensional sketch of venturi design.

The reduced mass flow from a venturi design is shown in figure 11. This figure gives mass flow rate, calculated as a function of projectile velocity using compressible flow equations, for inlet ducts of various shapes. Three ducts are compared: one with a 0.400-in.-diam* straight section, another with a 0.312-in.-diam straight section, and the third, a venturi with a 0.400-in.-diam inlet and a 0.312-in.-diam throat. As seen in figure 11, the 0.312-in.-diam duct has a mass flow considerably less than the 0.400-in-diam duct over the entire velocity range, whereas the venturi has the same mass flow as the larger duct in the low velocity region, but limits the mass flow rate by over 33 percent in the higher velocity region.

The resulting effect on alternator rotational speed using a venturi is shown in figure 12. This figure contains a plot of rotational speed versus

*(in.)2.54 = (cm)

simulated projectile velocity for a straight duct of 0.385-in. diam and for the venturi tube. A reduction in rotational speed of 33 percent compared with the straight inlet is achieved at the high velocities. The undercut turbine can be used with the venturi to achieve further speed reduction, as shown in figure 13.

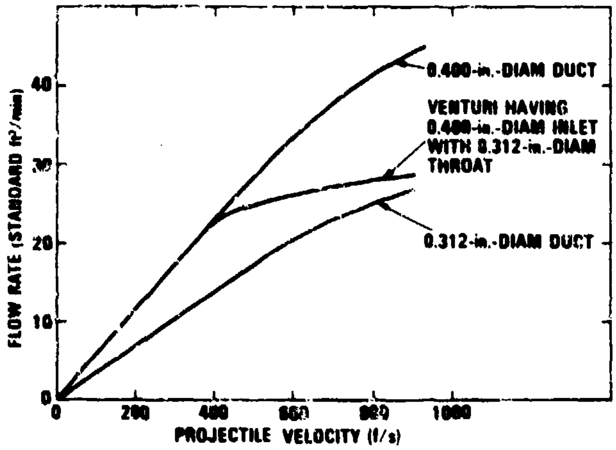

Figure 11. Effect of various inlet duct shapes on mass flow rate.

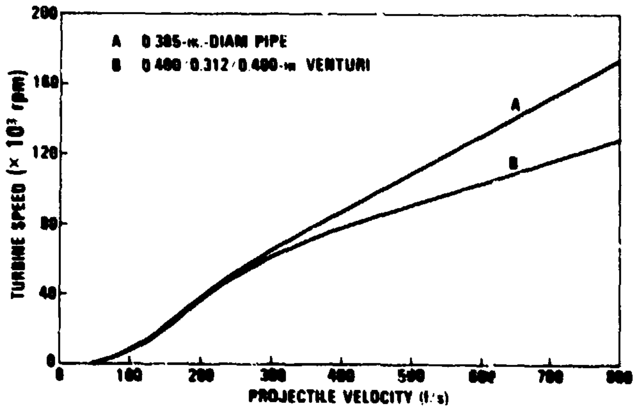

Figure 12. Rotational speed reduction of venturi compared with straight pipe over velocity range of 60-mm mortar.

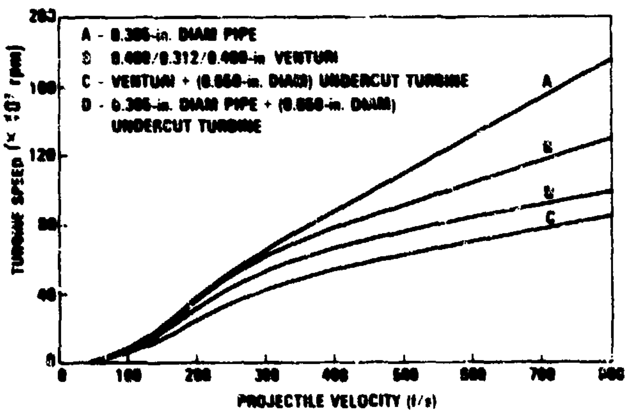

Figure 13. Comparison of several rotational speed reduction methods over velocity range of 60-mm mortar.

3.4 Brake Method

Another technique was developed. Undercut turbine blades were allowed to flex out under the influence of centrifugal force and rub against the alternator housing, resulting in a braking action. This approach was eliminated because it required tolerances between the turbine and the ogive that were impractical for high production.

4. VELOCITY DISCRIMINATION

Velocity discrimination is the dependence of alternator shaft rotational speed on projectile velocity. This can be achieved by designing the turbine blades and air channels so that the torque impulse produced is insufficient to turn the turbine until a minimum flight velocity is attained. Another approach is to adjust the attractive force between each magnet rotor pole and the corresponding stator pole. Both methods were required to meet electrical and power requirements for the 60-mm multi-option fuze for mortars. The turbine and inlet airflow had to be optimized at the low velocity extreme. Adjustment of rotor-stator attraction provided the necessary velocity discrimination.

Whenever a small angular displacement is applied, the attractive force between each magnet rotor pole and its magnetic image in the corresponding stator results in a restoring torque on the rotor. For rotation to begin, the restoring torque must be exceeded by an external mechanical torque applied to the rotor shaft. In the alternator for the multi-option fuze, the external torque is the reaction to the turning of the turbine blades by the inlet flow. As the projectile velocity, as simulated in the laboratory, is increased gradually, the starting velocity is defined as the projectile velocity at which the torque produced by the ram air exceeds the rotor stator attractive torque so that the shaft rotation begins. The rotor-stator attraction torque depends on the size and orientation of the rotor and stator poles, the airgap distance between the rotor and stator, leakage flux paths between the rotor and stator, and the state of magnetization of the rotor. Several methods of varying the rotor-stator attractive torque, and consequently the starting velocity, are described below. Test equipment used to investigate turbine/alternator starting charateristics is shown in figure 14. For these tests an alternator is mounted in a housing, as shown in figure 14, with its inlet port connected to a settling chamber. The pressure in the settling chamber is adjusted by a regulator. The simulated ram air velocities corresponding to settling chamber pressure from 0 to 1 psig* are calculated from Bernoulli's law for flow through a nozzle:

$$V = \sqrt{\frac{2\Delta p}{\rho}}$$

where Δp is the gauge pressure measured in the settling chamber, and ρ is the air density.

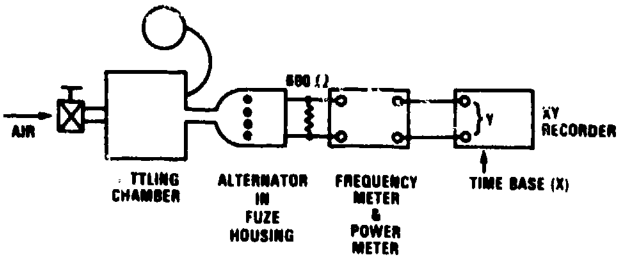

Figure 14. Apparatus used to measure alternator starting characteristics.

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*(psi)6.89 = (kPa). psig = differential pressure above ambient pressure of 14.7 psi.

For one to measure starting velocity, the pressure is gradually increased until the alternator shaft begins to spin. Then the velocity corresponding to the starting pressure is calculated as described above.

Figure 15 shows the effect of varying the stator-pole width. Reducing this width while holding all other parameters constant increases the starting velocity. Reducing the pole width from 0.250 to 0.230 in. increases the starting velocity from 35 to 90 ft/s.

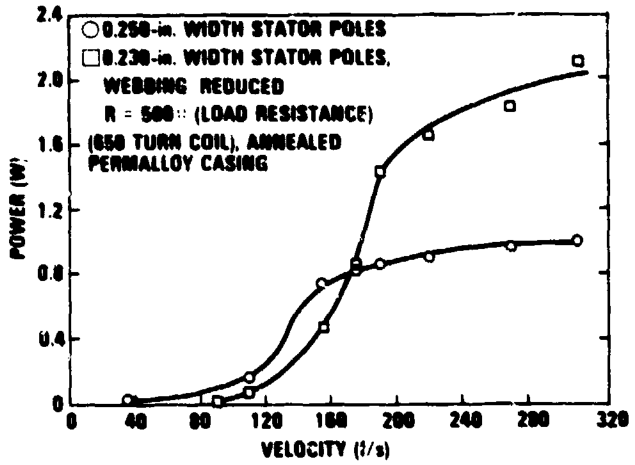
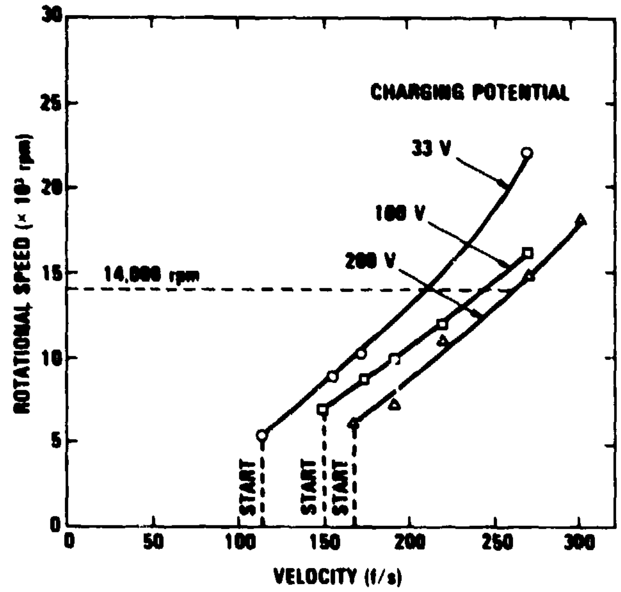


Figure 15. Effect of stator pole width on starting velocity and power output.

The state of magnetization of the rotors is determined by the voltage level set on a bank of capacitors in a pulse magnetizer used tc magnetize the magnets. Figure 16 shows the effect of charging voltage on inlet air velocity at which the alternator starts. As the charging voltage is increased from 33 to 100 V, and then to 200 V, the respective starting speeds increase to 115, 150, and 168 ft/s, respectively (fig. 16). Also the velocity required to achieve a given rotational speed, e.g., 14,000 rpm, increases as the charging voltage increases.

Figure 16. Effect of magnetizer charging voltage on alternator starting velocity.



5. REDUCTION OF ALTERNATOR SIZE

The dimensions of alternators can be reduced to allow more room for fuze electronics or to furnish small power supplies for submunitions applications. Low-cost manufacturing features of the alternator for the M734 fuze can be incorporated in these alternator designs.

An alternator having a two-pole rotor and two-pole stator casing has been assembled (fig. 17, bottom). Its magnetic circuit is the same as that of the alternator for the 60-mm fuze, except that only two flux loops link the coil instead of six (as shown in fig. 5). The stator pole height is 0.300 in., and the alnico rotor diameter is 0.300 in. The alternator, including turbine, fits a cylindrical space of 0.775-in. diam and 0.735-in. length, with a total volume of 1/3 in.^{3}. Figure 18 is a plot of power output versus rotational speed of this unit. This device develops a maximum of 0.8 W at 100,000 rpm and is suitable for a time fuze.

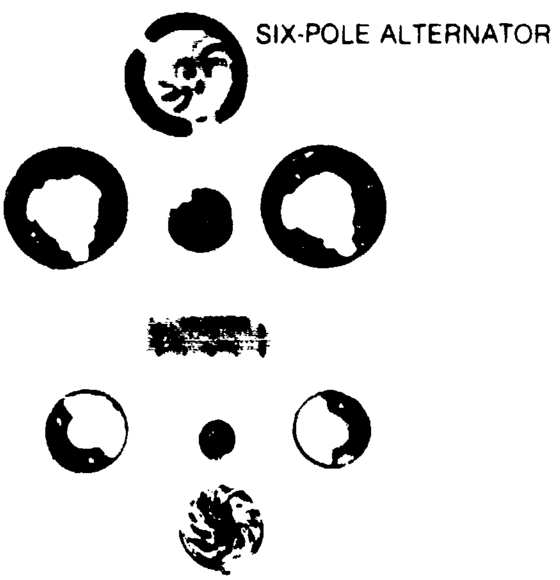


Figure 17. Two-pole alternator and six-pole alternator, emphasizing comparison of stators.

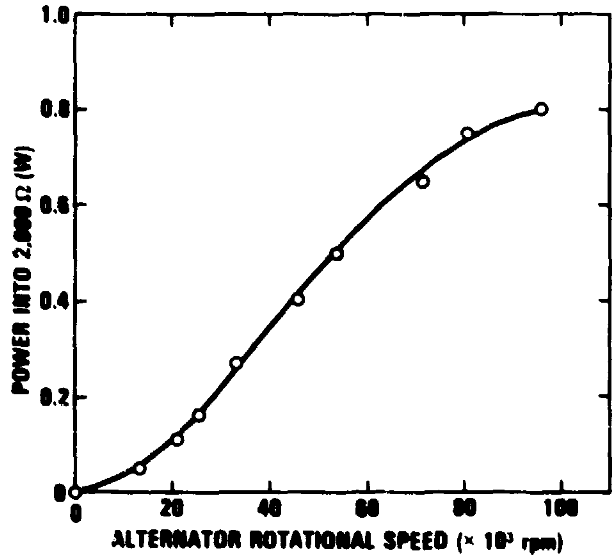


Figure 18. Power output versus rotational speed of small (1/3 in.^{3}) two-pole alternator using alnico rotor.

A four-pole design with a total volume of 1/4 in.^{3} was fabricated (fig. 19). The stator assembly is made of two identical permalloy end plates which fit inside a permalloy ring to complete the magnetic circuit; this assembly is similar to the alternator shown in figure 1. The rotor is a 0.300-in.-diam alnico type, magnetized radially with four poles. The stator poles are 0.250-in. wide × 0.237-in. high × 0.027-in. thick. The outer diameter of the assembled alternator is 0.732 in. and the length, including turbine, is 0.600 in. The advantage of this design over the two-pole configuration is that the

end plates can be stamped as required for large-quantity production. This alternator also employs inexpensive ball bearings which have a stamped retainer that serves as the outer race; the inner race is the shaft. The electrical output of this unit into a matched resistive load is plotted versus rotational speed in figure 20. The maximum power developed, 0.8 W, is the same as that of the two-pole alternator (figs. 17 and 18); however, this maximum is attained at a lower rotational speed of 60,000 rpm.

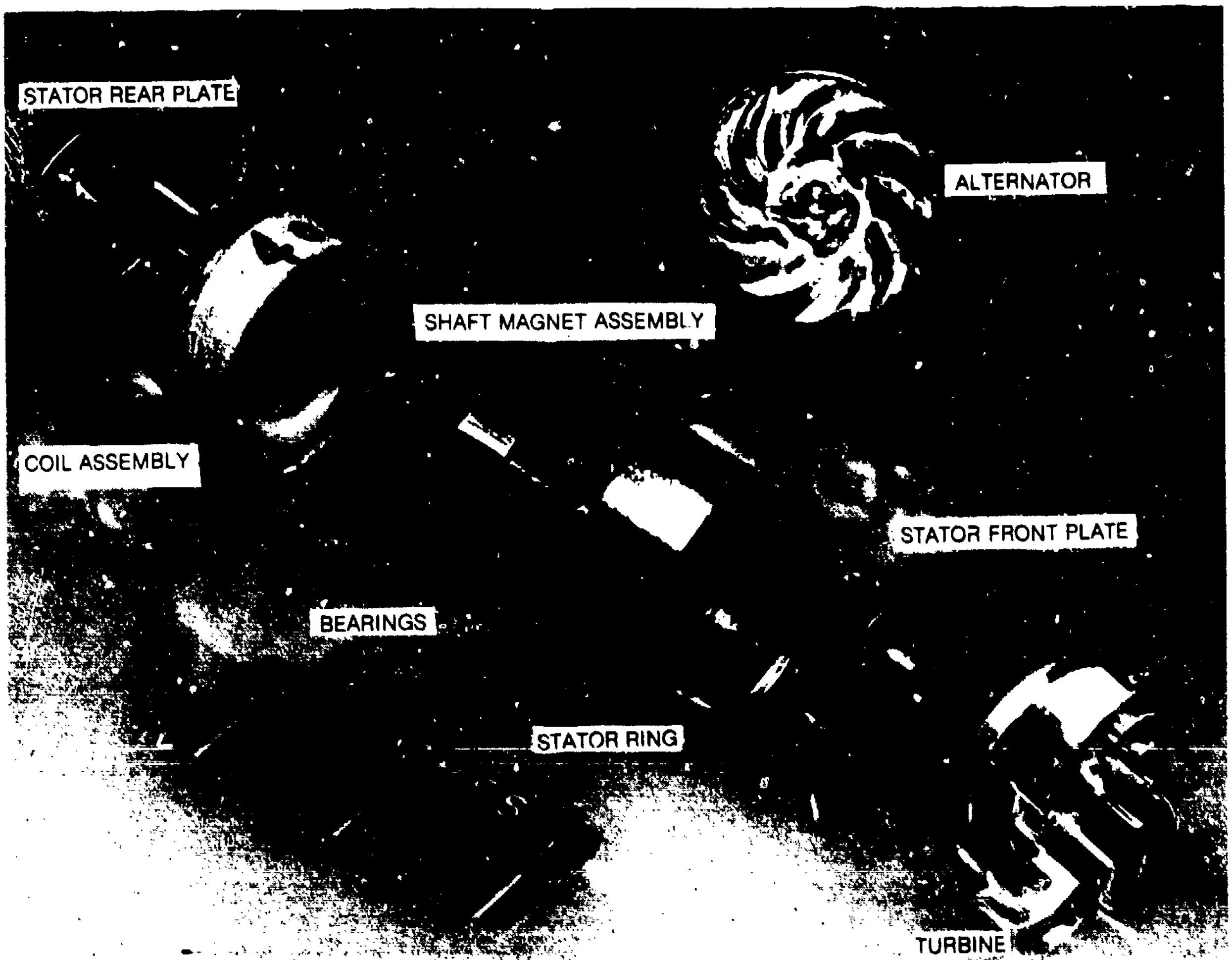


Figure 19. Small (1/4 in.^{3}) four-pole alternator (top) and components (bottom).

Figure 21 is a plot of power output versus velocity of the four-pole design. This curve shows that the maximum power of 0.8 W can be achieved at 180 ft/s. This power level is similar to that required by the M734 alternator. This device demonstrates the capability of making small alternators that can be produced in quantity.

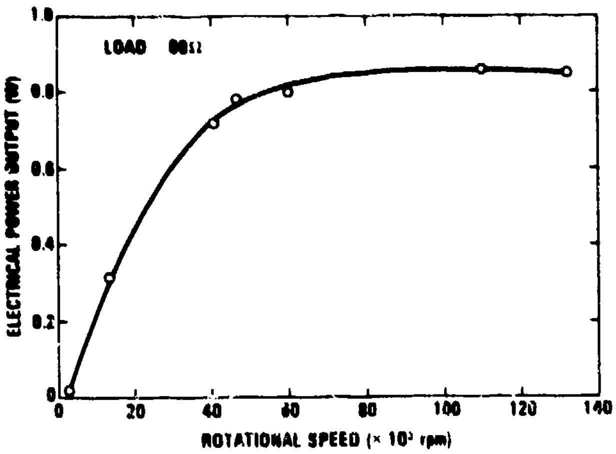


Figure 20. Power output versus rotational speed of small (1/4 in.^{3}) four-pole alternator using alnico rotor.

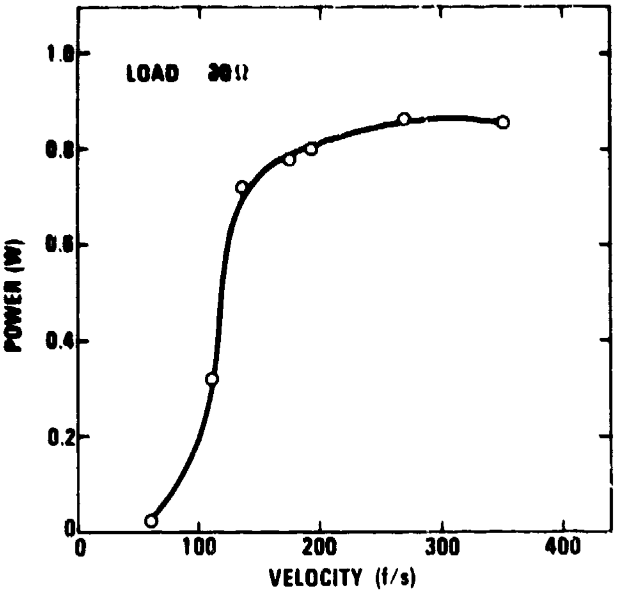


Figure 21. Power output versus velocity of small, four-pole alternator.

6. INCREASING ELECTRICAL OUTPUT WITH SAMARIUM-COBALT MAGNETS

Alloys of the ferromagnetic element cobalt and rare-earth elements such as samarium or praseodymium result in permanent magnets having properties superior to the more common alnicos, which are alloys containing aluminum, nickel, and iron.[5] Several properties relevant to alternator design are discussed below, followed by the results of an investigation to improve alternator output by use of samarium-cobalt rotors.

The maximum energy product, which is obtained from the demagnetization curve of the permanent-magnet material, is a measure of maximum energy available in an airgap per unit volume of the permanent-magnet material.[6] Other properties of permanent magnets, such leakage permeance and recoil permeability, allow only a small fraction of this energy to be used, even when the geometry is optimized. This suggests that if the fraction of energy used in an alternator application is the same for two different permanent-magnet materials of the same shape and equal volumes, the material having the higher energy product should produce greater power. For alnico 8, which has the highest maximum energy product of the alnico magnets, the maximum energy product is 5 MGOe (mega-gauss-oersteds),* compared with 23 MGOe for samarium

[5] *Joseph J. Becker, Permanent Magnets, Sci. Am., 223 No. 6 (December 1970), p 92.*

[6] *R. J. Parker and R. J. Studders, Permanent Magnets and their Applications, John Wiley and Sons, Inc., New York (1962), pp 32-34.*

*$(\text{gauss} \cdot \text{oersted}) 79.577 \times 10^{-4} = (\text{watts/m}^3)$

cobalt ($SmCo_5$). It therefore seems that replacing an alternator's alnico rotor with a samarium-cobalt rotor of the same shape and volume would increase the output power. It also seems possible to reduce the size of existing alternators operating at a given power level by using a smaller volume of $SmCo_5$ instead of alnico in the rotor.

Materials such as the alnicos are more susceptible to demagnetization than is $SmCo_5$.[7] The material $SmCo_5$ cannot be demagnetized readily, even under the influence of applied fields of up to 18 kOe.* If identical fully magnetized bars of $SmCo_5$ and alnico 8 are each inserted into a demagnetizing solenoid, a much greater current would be required to demagnetize $SmCo_5$ than to demagnetize alnico 8. The minimum current level required to demagnetize alnico 8, if applied to the magnetized $SmCo_5$, would not reduce the magnetization of the $SmCo_5$ noticeably below its maximum value (remanent magnetization).

In alternator applications, the current supplied by the stator coil to the electrical load acts as a demagnetizing force on the permanent magnet rotor. Hence, larger load currents should be obtainable in alternator applications using $SmCo_5$ instead of the alnicos.

A study was made to improve alternator performance by using the cobalt-rare-earth permanent magnets to replace alnico rotors. Although an improvement in performance was achieved, further improvement can be obtained by redesigning the stator configuration to take advantage of the difference in leakage flux properties between the cobalt-rare-earth materials and the alnicos.

Figure 22 shows an assembled two-pole alternator and its components. The stator is formed of two highly permeable casings. The casings are inserted one into the other and are attached to two aluminum end-plates which contain the bearings. The cylindrical magnet rotor is magnetized radially in two poles. The coil fits between the casings so that the flux passing through the coil reverses direction as the rotor spins under the influence of ram air which drives the turbine. In figure 23 the electrical power output into a matched resistive load is plotted versus rotational speed for two alternators: one employing a sintered alnico-2 rotor and the other employing a samarium-cobalt rotor of the same dimensions. In the alternator employing the alnico-2 rotor, the electrical power increases with rotational speeds up to 80,000 rpm. The power output appears limited at 6 W above 80,000 rpm. When the samarium-cobalt rotor is used, the power output is greater than that of the alnico 2, and it increases linearly with rotational speed. The power at 25,000 rpm is 11.2 W versus the 3.5-W power of the alnico rotor. However, the increased output is obtained with a greater expenditure of mechanical energy,

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[7] R. L. Ross, G. J. Iafrate, and F. Rothwarf, *Electromechanical Energy Conversion Devices Utilizing both Conventional and Rare-Earth Cobalt Permanent Magnet Materials*, US Electronics Command, RDTR ECOM 4064 (December 1972), p 4.

*(oersted)79.577 = (ampere/meter)

as evidenced by the higher air velocity required to start the samarium-cobalt alternator. The starting velocity is 480 ft/s as compared with 115 ft/s for the alnico-2 rotor.

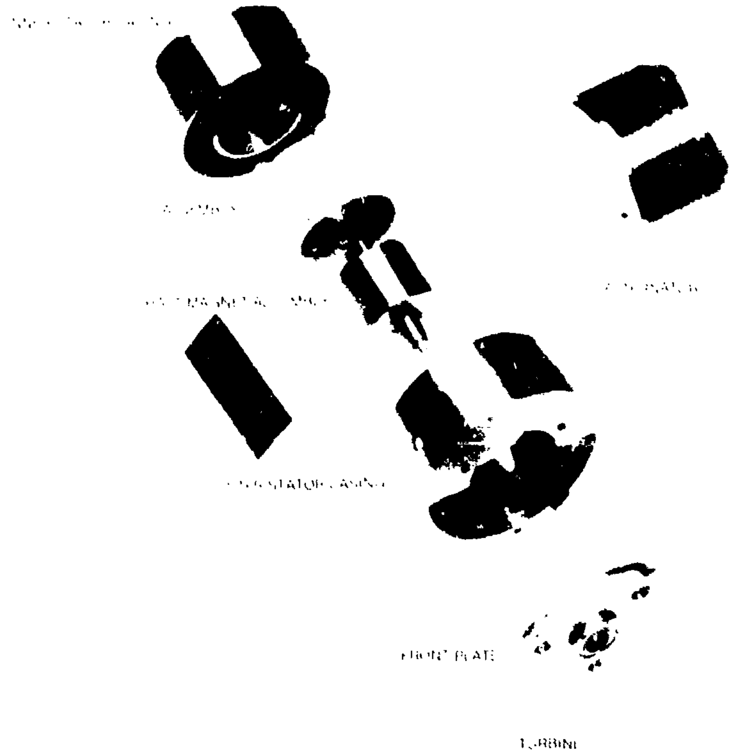

Figure 22. Large two-pole alternator (top) and components (bottom).

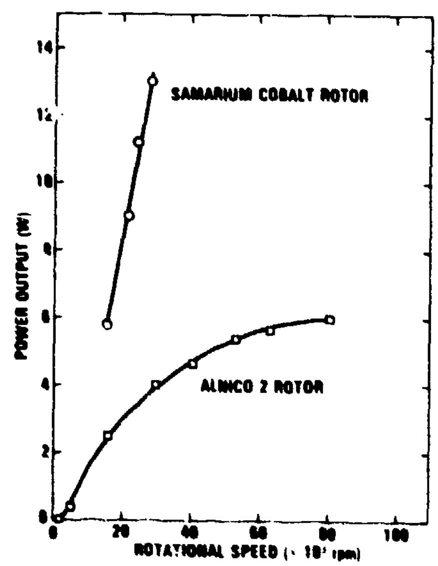

Figure 23. Comparison of electrical output of large two-pole alternator with alnico-2 rotor and samarium-cobalt rotor of same dimensions.

Figure 24 compares the electrical output of an alternator using a samarium-cobalt rotor with one using alnico 2; this is for a smaller version of the two-pole alternator with a 0.300-in.-diam rotor. The samarium-cobalt rotor produces a power output of 4.1 W in contrast to a maximum of 0.8 W obtained using the alnico rotor. Hence, the use of a samarium-cobalt rotor in place of an alnico-2 rotor permits higher electrical output to be obtained at a given rotational speed, provided that the additional torque is available to drive the rotor at that speed.

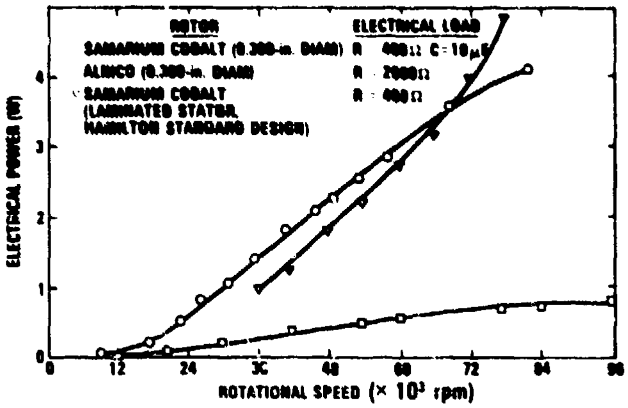

Figure 24. Comparison of electrical power output of small two-pole alternator with alnico-2 rotor and samarium-cobalt rotor.

An alternator using a two-pole samarium-cobalt magnet rotor but having a laminated two-pole stator was fabricated by Hamilton Technology.[8,9] The power output versus rotational speed of this alternator while it operates into a 400-Ω resistive load is plotted in figure 24 for comparison with the HDL alternator of similar size having a nonlaminated stator. Below 70,000 rpm, the HDL alternator produces greater electrical power than does the Hamilton device. Above 70,000 rpm the Hamilton alternator output is greater, being 4.8 W at 78,000 rpm compared with 4.0 W from the HDL unit.

The output of the nonlaminated HDL alternator is comparable to the laminated Hamilton alternator at the 4-W level when these devices are operating into a 400-Ω load. When operating into a 100-Ω load, the Hamilton alternator produces 7 W at 60,000 rpm. An unlaminated design can be more economical to manufacture, and because of its lower cost should be used in applications in which desired operating characteristics can be achieved.

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[8]*Tiny Alternator/Generator Uses Rare-Earth Magnetic Materials, Product Engineering*, 45 *(August 1974), pp 11, 13.*

[9]*Ray C. Carriker, Miniaturized Power Sources for Weapons, National Defense (March-April 1975).*

7. ELECTRICAL POWER REQUIREMENTS

HDL-designed alternators of the types previously discussed can be matched into required fuze loads by a coil having the proper number of turns and proper wire resistivity.[10] Figure 25(a) indicates power output versus simulated ram air velocity for various resistive loads. The coil used has 600 turns of no. 30 wire. If a velocity of 350 ft/s is arbitrarily selected as the velocity at which the designated output is required, then the matched load is 1,000 Ω. Replacing the coil with one having 2,100 turns of No. 36 wire (fig. 25(b)) results in a matched load between 10,000 and 20,000 Ω. Note that for either coil, the electrical power output at 350 ft/s into the matched load is the same 11.5 W.

Figure 25(a) shows that the dependence of electrical power on ram air velocity depends on the impedance of the load for a given coil. For a matched load of 1,000 Ω, the power increases linearly with velocities up to 340 ft/s and becomes constant above that speed. As the load resistance is decreased to 400 Ω, the power increases linearly with velocity but with a reduced slope. At the lower load resistance of 200 and 100 Ω, the power is independent of air velocity. Hence, proper selection of the load and coil impedances produces an alternator with constant output power.

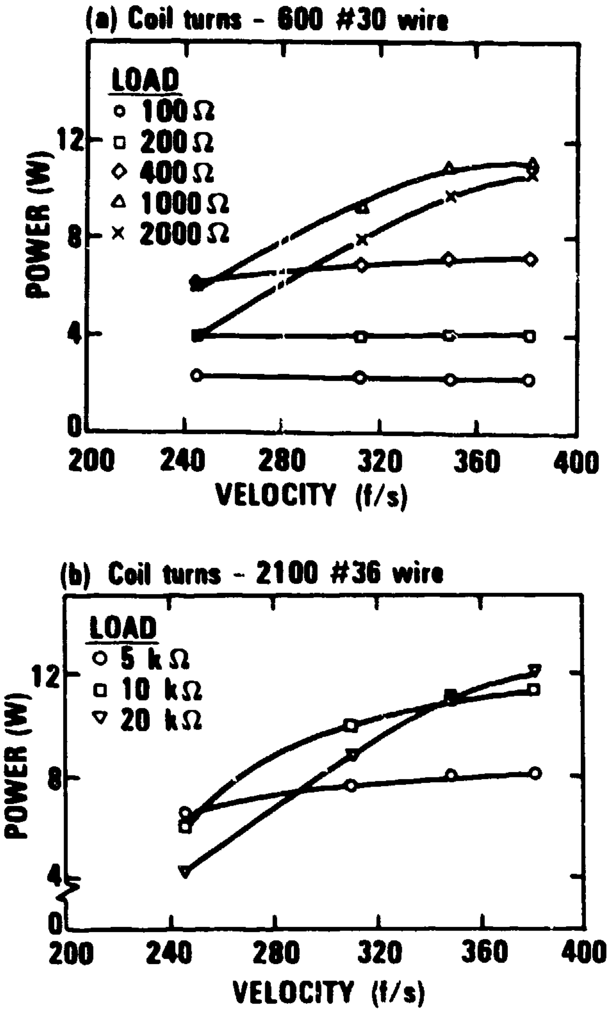

Figure 25. Effect of electrical load and coil on alternator power output.

8. FIELD TEST RESULTS ON SUITABILITY OF ALTERNATORS FOR FUZE ENVIRONMENTS

The ability of alternators developed at HDL to withstand harsh fuze environments has been proven in a wide range of field tests.

8.1 M734 Multi-Option Mortar Fuze Power Supply

The alternator for the Army multi-option fuze for mortars (fig. 1) has been fired successfully at charge zones up to charge 4,

[10] *Carl J. Campagnuolo and Jonathan E. Fine, High Power Alternator for Bomb Fuze Application, Harry Diamond Laboratories, HDL-TM-72-29 (November 1972), pp 18-21.*

which corresponds to a maximum acceleration of 10,000 g, and in all cases has produced the required mechanical and electrical energy for the fuze. The alternator, assembled in the fuze, has passed all MIL-STD requirements. To date 750,000 of these alternators have been produced.

8.2 Artillery Time Fuze Power Supply

A field test was conducted to verify the gun ruggedness of a small, two-pole alternator, (fig. 26) designed to power a time fuze.* The alternator employs several speed regulation features and several methods for surviving ruggedness for the artillery launch environment. The stators are designed to be supported during setback by the end plate to withstand setback forces. This is accomplished by allowing the stator pole-pieces made from permalloy 49 to rest on the aluminum end-plates. Because aluminum is not a permeable material, the magnetic flux from the rotor is not diverted from its designated path within the magnetic circuit.

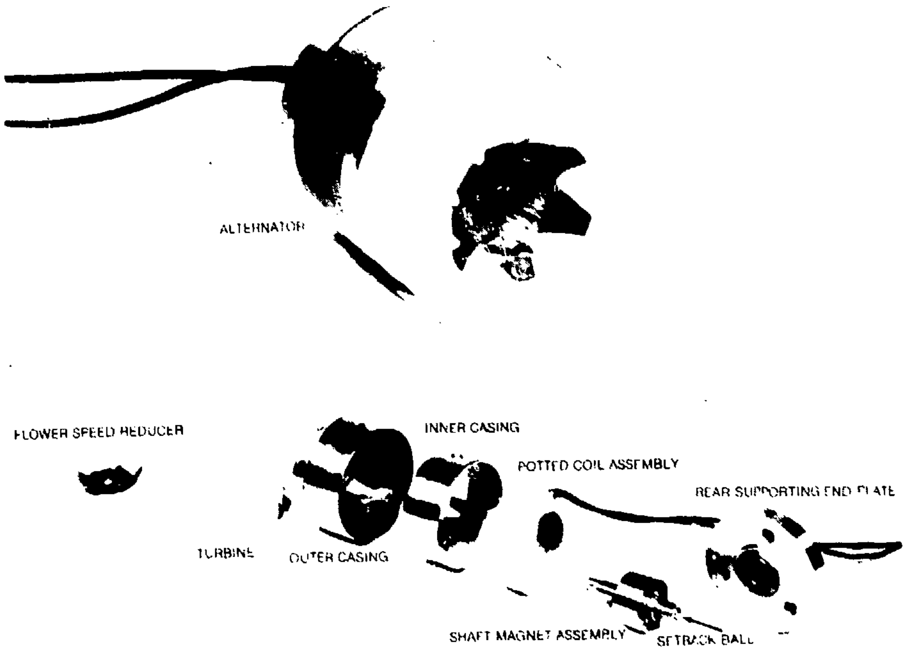

Figure 26. Two-pole alternator for artillery time fuze showing alternator (top) and components (bottom).

The alternator shaft is mounted between two ball bearings: one mounted in the front plate, and the other in the rear. The rear of the alternator shaft is counter-bored to house a small hardened steel ball that rests on the rear aluminum plate. During setback, the shaft is supported by the ball and rear plate. The ball preserves the ball bearings and allows the shaft to rotate. The coil windings are embedded in a potting compound that fills the spaces between the wires and prevents motions that can cause the breaking of the wires during setback and flight. These design features have

*Jonathan E. Fine and Floyd Allen, *Field Test of Ram Air-Driven Alternator Power Supply for Artillery Fuze*, Harry Diamond Laboratories internal report (7 August 1980).

produced a very rugged alternator design; its ruggedness was verified before field testing by air-gun tests.

8.2.1 Features that Limit Shaft Rotational Speed

The turbine used in the artillery time-fuze power supply is similar to that used in the alternator power supply for the M734. This turbine is very efficient at low projectile velocity and has a blade undercut that allows the blades to expand and reduce the rotational speed at high projectile velocity. The mortar travels at a maximum of 800 to 1000 ft/s. Artillery projectile velocities are as high as 3000 ft/s; hence, reduction in rotational speed is desired to conserve bearing life. For this purpose, a metal disk having five fingers is mounted on the turbine to reduce the flow to the turbine blades. A venturi in the air inlet also aids in limiting rotational speed by reducing the inlet flow. This combination of methods has proven very effective in limiting the alternator rotational speed at high velocity and yet not diminishing the device's ability to perform at the higher altitude portion of flight trajectories, where the availability of air energy is reduced.

Because the quantity of permanent magnet material was reduced to achieve a lighter, more rugged rotor, the electrical output of the two-pole alternator is limited to about 0.7 W into a simulated fuze load of 2000 Ω. This is sufficient to power an electronic time fuze.

8.2.2 Field Test Results

After the alternator ruggedness had been established in the laboratory by air-gun setback tests up to 17,000 g and spin tests up to 300 rotations/s (the maximum expected in flight), a field test was conducted using the 75-mm pack howitzer as a test vehicle.

The method was to telemeter the rectified voltage output of the alternator when fired from the weapon. The gun was fired at 15 deg launch elevation and produced flights of 15- to 18-s duration, a setback of 17,000 g, and a spin of 15,000 rpm. The objective of the test was to obtain sufficient data during flight to show that the alternator had survived the gun environment. A special telemetry system was constructed for the field test. It contained a nickel-cadmium rechargeable battery power supply that could be turned on immediately before the flight. Figure 27 shows the electrical output of alternators 2, 9, and 10, for which data were obtained throughout the flight. In the figure, normalized voltage (which is proportional to normalized subcarrier-control oscillation (SCO) frequency) is plotted versus flight time. The maximum value of the voltage occurred 0.2 s into flight, consistent with the expectation that the maximum value is reached at muzzle exit. During the later portion of the flight, the data were nearly constant, between 80 and 85 percent of the maximum value. This indicates some reduction in voltage later in the flight, possibly as a result of increased friction from deformation sustained by the shaft support system during setback. The test indicates that the shaft support system protected the ball bearings from damage during setback. These test results also indicate that the speed regulation was very effective up to the muzzle velocity of 1250 ft/s achieved in the test.

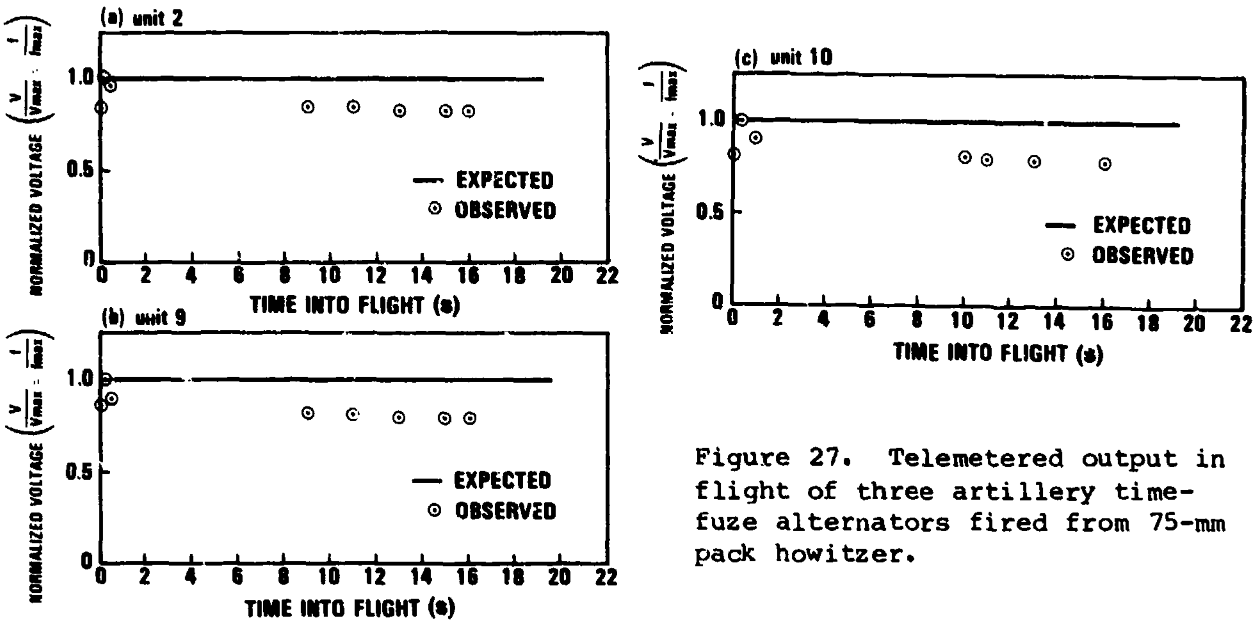

Figure 27. Telemetered output in flight of three artillery time-fuze alternators fired from 75-mm pack howitzer.

9. SUMMARY

The basic alternator design developed for the multi-option fuze for mortars has been modified to meet the requirements of other fuzing applications while maintaining the simplicity of design required for quantity production.

The need to limit rotational speed to maintain the required safe-arming distance and to reduce bearing wear has resulted in the development of several methods of achieving speed limitation by a combination of mechanical and aerodynamic means. The most promising method uses undercut turbine blades which flex out radially, reducing the turning angle of fluid passing through the blades. This method is incorporated into the turbine itself at no additional manufacturing cost.

Velocity discrimination can be achieved by adjustment of airflow passages by use of a venturi configuration and also by use of the attraction between rotor and stator poles. The attraction is adjusted by using the stator pole dimensions in combination with the magnetizing voltage used to magnetize the rotor.

An alternator having a volume of 0.25 $in.^3$ was designed with a four-pole stator and four-pole alnico rotor; this alternator produced 0.8 W electrically. It can be produced in quantity by the same means as the mortar fuze alternator and has the same electrical output as a two-pole design of the same size.

The use of a samarium-cobalt rotor in place of an alnico-2 rotor in both a larger two-pole and smaller two-pole alternator design showed that four times the electrical output was obtained at similar rotational speeds with the

samarium-cobalt rotor. This could be useful provided that the additional mechanical torque is available to turn the turbine.

Flight tests on an artillery fuze alternator fired from a 75-mm pack howitzer demonstrated the suitability of alternators where setback forces of up to 17,000 g are experienced at high spin rates.

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